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14. ABSTRACT
Our research is primarily focused on the development, analysis and verification of robust adaptive control algorithms for nonaffine-in-control nonlinear systems. In particular, we are interested in the development of methodologies that operate in the presence of sensor noise and provide robustness to modelling and environmental uncertainties, such as a battle damage or a control surface malfunction. Of special interest are design methods that would enable control of distributed parameter systems with reduced order controllers, appropriate for active aerodynamic flow control. These objectives are being addressed in close collaboration with industry and government labs in order to enable rapid transition of our research results to problems of high value for the Air Force and the aerospace industry.

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FINAL REPORT

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Objectives

Our research is primarily focused on the development, analysis and verification of robust adaptive control algorithms for nonaffine-in-control nonlinear systems. In particular, we are interested in the development of methodologies that operate in the presence of sensor noise and provide robustness to modelling and environmental uncertainties, such as a battle damage or a control surface malfunction. Of special interest are design methods that would enable control of distributed parameter systems with reduced order controllers, appropriate for active aerodynamic flow control. These objectives are being addressed in close collaboration with industry and government labs in order to enable rapid transition of our research results to problems of high value for the Air Force and the aerospace industry.

Status of Effort

Our main accomplishments of the past year can be summarized as follows: a) an approximate dynamic inversion methodology is developed for *nonaffine-in-control* nonlinear systems using time-scale separation; b) a *new* parameterization of adaptive controllers is developed that completely *avoids* the input saturation; c) a methodology is suggested for autonomous aerial refuelling using techniques from differential games and adaptive control. These problems were motivated and fully supported by government labs and industry. Below we briefly summarize the main ideas, results and demonstrate example simulations.

Accomplishments

Approximate dynamic inversion of nonaffine nonlinear systems via time-scale separation.

Control design methods for nonaffine systems are motivated by a variety of applications that employ novel actuation devices, which are nonlinearly coupled to the dynamics of processes they are intended to control. Among the aerospace applications a benchmark problem is presented by a flying vehicle, the aerodynamic control effectiveness of which depends *nonlinearly* upon its control surface positions. An approximate dynamic inversion methodology is developed for a class of *nonaffine-in-control* systems using time-scale separation [J1]. The control signal is sought as a solution of fast dynamics and ensures exponential stabilization and tracking for the original nonaffine system dynamics. A constructive algorithm is developed for multivariable systems. Sufficient conditions are derived, and a few instances for their verification are proposed

in [J1]. The plots in Fig. 1 show the numerical simulation results for tracking series of consecutive step-inputs applied to the following nonaffine-in-control system:

$$\begin{aligned}
\dot{x}_1(t) &= x_2(t) \\
\dot{x}_2(t) &= x_1(t)e^{x_2(t)} + u(t) + (u(t))^2 \tanh(u(t)) \\
\dot{z}(t) &= -z(t) - ((x_1(t))^2 + (x_2(t))^2)(z(t))^3.
\end{aligned}$$

In order to approximate on-line the exact dynamic inversion controller, fast dynamics is introduced as:

$$\epsilon \dot{u} = -\text{sign}\left(\frac{\partial f}{\partial u}\right)(x_1 e^{x_2} + u + u^2 \tanh(u) + \dot{x}_m + x_m - br), \;\; u(0) = u_0$$

It can be verified that the on-line approximation ensures tracking of the reference model $\ddot{x}_m(t) = -\dot{x}_m(t) - x_m(t) + r(t)$, where $r(t)$ denotes the series of step inputs.

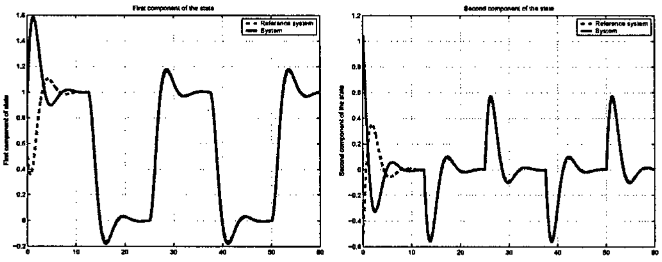


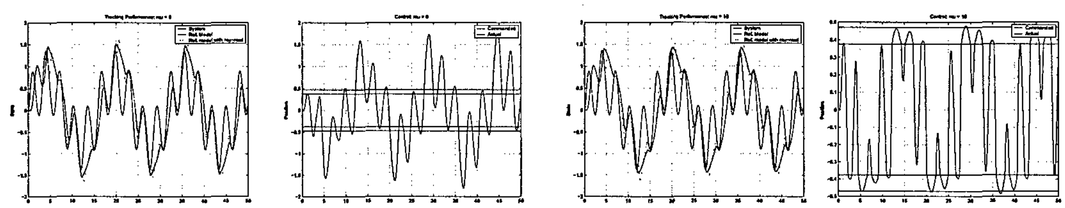
Fig. 1 Tracking performance.

During the next year, we will explore an extension of the idea to adaptive control frameworks for uncertain systems, in which the modeling error explicitly depends upon the control input. This will enable us to perform a one-to-one comparison with the existing alternative control methodologies in the literature (e.g. dynamic extension based on differentiation of the control signal).

Adaptive control in the presence of input constraints.

Development of integrated adaptive control methods for compensation of actuator failures requires a framework that accounts for input constraints in multivariable systems and, if required, prevents the hard saturation overall. During the past year we have developed a method for a class of dynamical systems with unknown parameters and matched uncertainties that ensures stable adaptation in the presence of input constraints [J5-J7, C4]. The method implies adaptive modification of the reference input depending upon control deficiency. The proposed design methodology, termed "positive μ-modification", *protects the control law* from actuator position saturation. Moreover, the new parameterization of the adaptive controller allows for explicit reduction of the control deficiency, consequently affecting the second derivative of the control signal. This, in its turn, is crucial for preventing interaction with structural modes during the periods of saturation. The design is Lyapunov based and ensures global asymptotic tracking for open-loop stable systems. For unstable systems an estimate for the domain of attraction is derived based on the input saturation magnitude and system parameters. Fig. 2 demonstrates the closed-loop tracking performance and control deficiency for two values of μ in the scalar system $\dot{x} = 0.5x + 2u$, subject to the following actuator constraint $u_{\max} = 0.47$. The reference model without μ-modification is given as $\dot{x}_m = -6x_m + 6r$ along with the reference input $r = 0.7(\sin(2t) + \sin(0.4t))$. The plots confirm the theoretical results.

During the next year, our efforts will be focused on the extension of the methodology to multivariable systems, incorporating both magnitude and rate saturation. Extension to nonaffine nonlinear systems will also be addressed.



a) $\mu = 0$, tracking **b)** $\mu = 0$, control **c)** $\mu = 10$, tracking **d)** $\mu = 10$, control

Fig. 2 Tracking performance and control deficiency for $\mu = 0$ and $\mu = 10$.

Aerial Refuelling Autopilot Design.

An application of the existing adaptive control methodologies to the aerial refuelling problem is addressed. The hose-and-drogue aerial refuelling system is considered for the nonlinear longitudinal model of the F-16 aircraft under the assumption that the drogue coordinates are measured with sufficient accuracy [C2, C11].

It is assumed that the tanker is in steady level flight and the coordinates of the drogue, moving in the vertical plane, are available as measurements. For the relative longitudinal motion of the receiver aircraft a linear reference model is considered, which is used for baseline optimal control design using methods from *differential game* theory. The reference model with the *optimal control* generates a *nonlinear reference model*, which is used as a reference trajectory. The control signal for the trailer aircraft is composed of an open-loop signal, defined by this optimal control law, an additional linear signal to obtain a closed loop Hurwitz matrix for the state space representation of the error dynamics in the absence of uncertainties, and an adaptive signal to compensate for the hose-drogue modeling uncertainties and its dynamic coupling with the receiver aircraft. Although the obtained results are quite preliminary, they illustrate the advantages and the potential for combining the differential game framework with adaptive techniques while solving the tracking problem in highly uncertain environments. Fig. 3 shows the tracking performance of the nonlinear reference model closed via an optimal control with and without the adaptive augmentation.

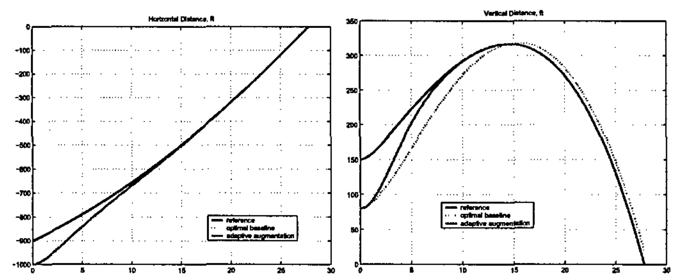


Fig. 3 Tracking performance in an aerial refuelling maneuver

Other accomplishments due to collaborations.

Adaptive output feedback control of a cable-mass system. Adaptive output feedback control approach, developed in [J16], is applied to a discretized model of a cable-mass system, subject to disturbances [C10, J2]. Specifically, this problem involves the vibrations of an elastic cable which is fixed at one end and attached to a mass at the other. The mass is suspended by a spring which has nonlinear stiffening terms and is forced by a sinusoidal disturbance. The problem of regulation of the mass is considered using a reduced order adaptive output feedback controller, and the results are compared to those obtained within the linear systems theory.

Control of autonomous underwater vehicle (AUV). Adaptive output feedback control approach, developed in [J16], is applied to an uncertain model of an underactuated underwater

vehicle. The vehicle is modeled as a neutrally buoyant, prolate spheroid moving in the longitudinal plane. The two inputs are the thrust along the symmetry axis and the pitch moment [J13].

Neural Network adaptive output feedback control for intensive care unit sedation and intraoperative anesthesia. Neural network based adaptive output feedback control is applied to control the infusion of the anesthetic drug propofol for maintaining a desired constant level of depth of anesthesia for noncardiac surgery [C3, J15]. These results present an extension of [C8, J9, J10].

Modelling and vibration control of thermoelastic plate in an electromagnetic field. Nonlinear equations of thermoelastic plate in an electromagnetic field are developed with consideration of a material nonlinearity [J2, C1]. Using Maxwell's equations for electromagnetic field, the modified Fourier law of heat conduction and elastokinetic field equations, the three-dimensional coupled problem is reduced to a two-dimensional one, appropriate for plates. Existence and uniqueness of the solution of a system of nonlinear partial differential equations is proved, arising from the modelling of current carrying thermoelastic plate-strip in a longitudinal magnetic field. Furthermore, a discretized model of the system dynamics is controlled using the adaptive output feedback control methodology from [J16].

Personnel Supported

Part-time postdoctoral fellow I. Tuzcu (11/03- 04/04), Research Associate A. Sasane (11/03- 06/04)

Interactions

Motivation for some of the problems came up from interactions with Dr. R. Albanese of AFRL/HE. Several problems have been entertained by Dr. E. Lavretsky from The Boeing Company, and the results were developed in close collaboration with him. Throughout the year, we have been interacting with J. Evers, AFRL/MNGN (Eglin AFB). We have been also interacting with Dr. Y. Ikeda from the Boeing Company on minimum distance optimal control problem in air traffic collision avoidance problem. We have had several technical discussions with Profs. A. Tannenbaum and W. Haddad from Georgia Tech. Collaboration with Profs B. King from Oregon State University and C. Woolsey from Virginia Tech are gratefully acknowledged.

Transitions (planned)

The control methodologies for nonaffine control systems and for adaptive control with input saturation, developed in close collaboration with Dr. E. Lavretsky from the Boeing Company, are planned for transition into Boeing applications. However, there are no transitions to date to report.

Points of contact:

1. R. Albanese, Ph.D., AFRL/HE, E-mail: Richard.Albanese@brooks.af.mil, Ph:(210)536-5710
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3. J. Evers, AFRL/MNGN 101 W. Eglin Blvd., Ste. 212 Eglin AFB, FL 32542-6810, Ph: (850) 882-2961 x2347, E-mail: johnny.evers@eglin.af.mil

Patent application in progress by The Boeing Company

"Adaptive Control in the Presence of Input Constraints" (with E. Lavretsky).

Honors

MARQUIS "Who is Who in Science and Engineering", VIII Edition, Dec. 2004.
Pride@Boeing award, 2004.

Selected Publications

Journal publications/submissions

J1. N. Hovakimyan, E. Lavretsky, A. Sasane, Approximate Dynamic Inversion for Nonaffine in Control Systems via Time-Scale Separation, Submitted to *System and Control Letters*, 2004.

J2. B. King, N. Hovakimyan, K. Evans, M. Buhl, Reduced Order Controllers for Distributed Parameter Systems: LQG Balancing and an Adaptive Approach, Submitted to Special Issue of *Mathematical and Computer Modeling*, dedicated to the 50th anniversary of AFOSR, 2004.

J3. D. Hasanyan, N. Hovakimyan, A. Sasane, Modeling and Analysis of Nonlinear Thermoelastic Plate Vibrations in an Electromagnetic Field, Submitted to *Proceedings of the Royal Academy of Sciences*, 2004.

J4. N. Hovakimyan, E. Lavretsky, A. Calise, R. Sattigeri, Decentralized Adaptive Output Feedback Control via Input/Output Inversion, Submitted to *IEEE Transactions on Systems, Man, Cybernetics*, 2004.

J5. E. Lavretsky, N. Hovakimyan, Positive μ-modification for Stable Adaptation in Dynamic Inversion Based Adaptive Control with Input Constraints, Submitted to *Automatica*, 2004.

J6. E. Lavretsky, N. Hovakimyan, Positive μ-modification for Stable Adaptation in the Presence of Input Constraints, Submitted to *IEEE Transactions on Automatic Control*, 2003.

J7. E. Lavretsky, N. Hovakimyan, Positive μ-modification for Stable Adaptation in a Class of Nonlinear Systems with Actuator Constraints, Submitted to *International Journal of Adaptive Control and Signal Processing*, 2003.

J8. N. Hovakimyan, E. Lavretsky, B.-J. Yang, A. Calise, Coordinated Decentralized Adaptive Output Feedback For Control of Interconnected Systems, To appear in *IEEE Transactions on Neural Networks*, vol.16, No.1, 2005.

J9. T. Hayakawa, W. Haddad, J. Bailey, N. Hovakimyan, Passivity-Based Neural Network Adaptive Output Feedback Control for Nonlinear Nonnegative Dynamical Systems. Accepted in *IEEE Transactions on Neural Networks*, 2003.

J10. T. Hayakawa, W. Haddad, N. Hovakimyan, V. Chellaboina, Neural Network Adaptive Control for Nonlinear Nonnegative Dynamical Systems, Accepted in *IEEE Transactions on Neural Networks*, 2002.

J11. A. Kutay, A. Calise, M. Idan, N. Hovakimyan, Experimental Results on Adaptive Output Feedback Control using Laboratory Model Helicopter. Accepted for publication in *IEEE Transactions on Control Systems Technology*, 2003.

J12. M. Idan, A. Calise, N. Hovakimyan, An Adaptive Output Feedback Control Methodology: Theory and Practical Implementation Aspects, *AIAA Journal of Guidance, Control and Dynamics*, vol. 27, No.4, pp. 710-715, 2004.

J13. E. Lavretsky, N. Hovakimyan, A. Calise, Upper Bounds for Approximation of Continuous-Time Dynamics Using Delayed Outputs and Feedforward Neural Networks, *IEEE Transactions on Automatic Control*, vol. 48 (9), pp.1606-1610, 2003.

J14. N. Hovakimyan, A. Calise, N. Kim, Adaptive Output Feedback Control of Uncertain Multi-Input Multi-Output Systems Using Single Hidden Layer Neural Networks, Submitted to *International Journal of Control*, 2004.

J15. W. Haddad, J. Bailey, T. Hayakawa, N. Hovakimyan, Neural Network Adaptive Output Feedback Control for Intensive Care Unit Sedation and Operating Room Hypnosis, Submitted to

Special Issue of *SIAM Journal of Control and Optimization* on Control Problems in Pharmacology, 2003.

J16. N. Hovakimyan, B.-J. Yang, and A.J. Calise, Robust adaptive output feedback control methodology for non-minimum phase systems, Submitted to Automatica, 2003, also appeared in In *Proceedings of the* 41^{st} *IEEE Conference on Decision and Control* 2002.

Conference publications/submissions

C1. D. Hasanyan, N. Hovakimyan, A. Sasane, V. Stepanyan, Adaptive Control and Analysis of Thermoelastic Plate Equations, in Proceedings of *43rd IEEE Conference on Decision and Control*, 2004.

C2. V. Stepanyan, E. Lavretsky, N. Hovakimyan, Aerial Refueling Autopilot Design Methodology: Application to F-16 Aircraft, In Proceedings of *AIAA Guidance, Navigation and Control Conference*, 2004.

C3. T. Hayakawa, W. Haddad, N. Hovakimyan, J. Bailey, Neural Network Adaptive Dynamic Output Feedback Control for Nonlinear Nonnegative Systems Using Delayed Outputs, In Proceedings of *American Control Conference*, 2004.

C4. E. Lavretsky, N. Hovakimyan, Positive -modification for Stable Adaptation in the Presence of Input Constraints, In Proceedings of *American Control Conference*, 2004.

C5. N. Hovakimyan, E. Lavretsky, B.-J. Yang, A. Calise, Decentralized Adaptive Output Feedback for Control of Large-Scale Systems using Neural Networks, In Proceedings of *American Control Conference*, 2004.

C6. N. Kim, A. Calise, N. Hovakimyan, Several Extensions in Methods for Adaptive Output Feedback Control, In Proceedings of *American Control Conference*, 2004.

C7. B.-J. Yang, A. Calise, N. Hovakimyan, Augmenting Adaptive Output Feedback Control to an Uncertain Nonlinear System with Actuator Nonlinearities, In Proceedings of *American Control Conference*, 2004.

C8. T. Hayakawa, W. Haddad, J. Bailey, N. Hovakimyan, Passivity-Based Neural Network Adaptive Output Feedback Control for Nonlinear Nonnegative Dynamical Systems. In Proceedings of *42nd IEEE Conference on Decision and Control*, 2003.

C9. N. Hovakimyan, E. Lavretsky, A. Calise, R. Sattigeri, Decentralized Adaptive Output Feedback Control via Input/Output Inversion, In Proceedings of *42nd IEEE Conference on Decision and Control*, 2003.

C10. B.B. King, N. Hovakimyan, An Adaptive Approach to Control of Distributed Parameter Systems, In Proceedings of *42nd IEEE Conference on Decision and Control*, 2003.

C11. V. Stepanyan, E. Lavretsky, N. Hovakimyan, A Differential Game Approach to Aerial Refueling Autopilot Design, In Proceedings of *42nd IEEE Conference on Decision and Control*, 2003.

C12. B.-J. Yang, N. Hovakimyan, A. Calise, Output Feedback Control of an Uncertain System using an Adaptive Observer, In Proceedings of *42nd IEEE Conference on Decision and Control*, 2003.

C13. A. Melikyan, N. Hovakimyan, Y. Ikeda, Dynamic Programming Approach to a Minimum Distance Optimal Control Problem, In Proceedings of *42nd IEEE Conference on Decision and Control*, 2003.